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UK Patent Application (19) GB (11) 2 217 458 (13) A

(43) Date of A publication 25.10.1989

(21) Application No 8907686.3

(22) Date of filing 05.04.1989

(30) Priority data
(31) 183872   (32) 19.04.1988   (33) US

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(51) INT CL⁴
G01V 1/36

(52) UK CL (Edition J)
G1G GEL G3P

(56) Documents cited
None

(58) Field of search
UK CL (Edition J) G1G GEL
INT CL⁴ G01V 1/28 1/30 1/32 1/34 1/36 1/37

(54) A method of enhancing and evaluating seismic data to suppress both random and coherent noise

(57) A method is provided for enhancing and evaluating seismic data. More particularly, a novel method is described for enhancing and evaluating common depth point seismic data. Common depth point (CDP) gathers of seismic signals are processed as shown in Fig 1 to suppress random noise and coherent noise and to enhance primary reflection events while preserving geologically- induced amplitude variations as a function of range for the primary reflection events. The processed CDP gathers of seismic signals can then be used to obtain attributes from which formation lithology and fluid content can be determined
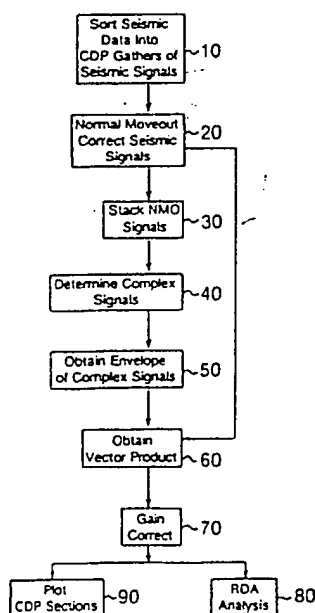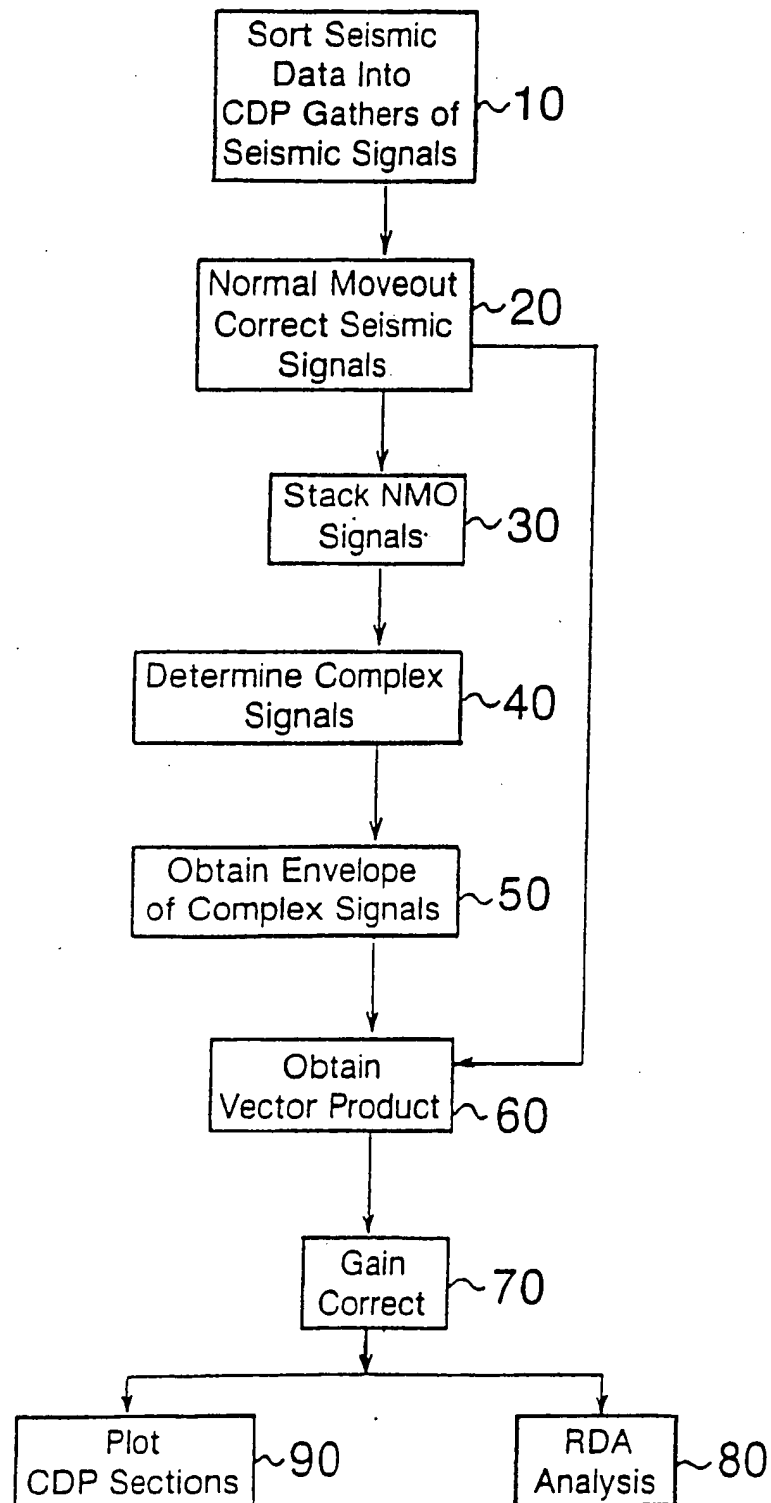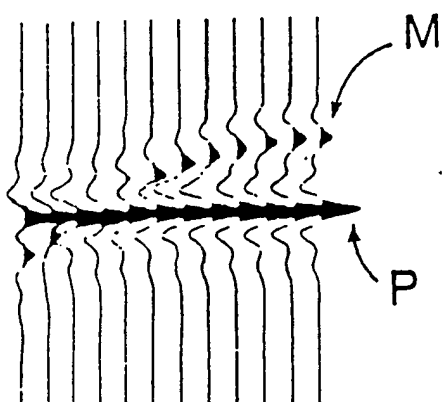

FIG. 1

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         ┌─────────────┐
         │Sort Seismic │
         │Data Into    │
         │CDP Gathers of│~10
         │Seismic Signals│
         └─────────────┘
               │
               ▼
         ┌─────────────┐
         │Normal Moveout│~20
         │Correct Seismic│
         │Signals      │
         └─────────────┘
               │
               ▼
         ┌─────────────┐
         │Stack NMO    │
         │Signals·     │~30
         └─────────────┘
               │
               ▼
         ┌─────────────┐
         │Determine Complex│~40
         │Signals      │
         └─────────────┘
               │
               ▼
         ┌─────────────┐
         │Obtain Envelope│
         │of Complex Signals│~50
         └─────────────┘
               │
               ▼
         ┌─────────────┐
         │Obtain       │
         │Vector Product│~60
         └─────────────┘
               │
               ▼
         ┌─────────────┐
         │Gain         │~70
         │Correct      │
         └─────────────┘
               │
        ┌──────┴──────┐
        ▼             ▼
  ┌──────────┐   ┌──────────┐
  │Plot      │   │RDA       │~80
  │CDP Sections│~90 │Analysis  │
  └──────────┘   └──────────┘
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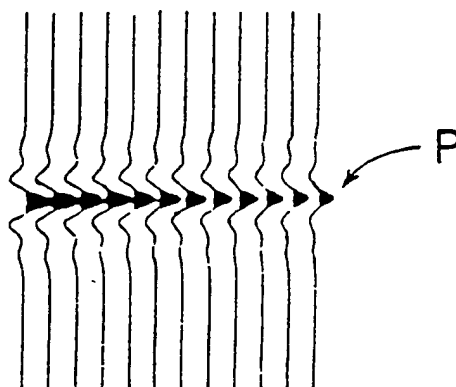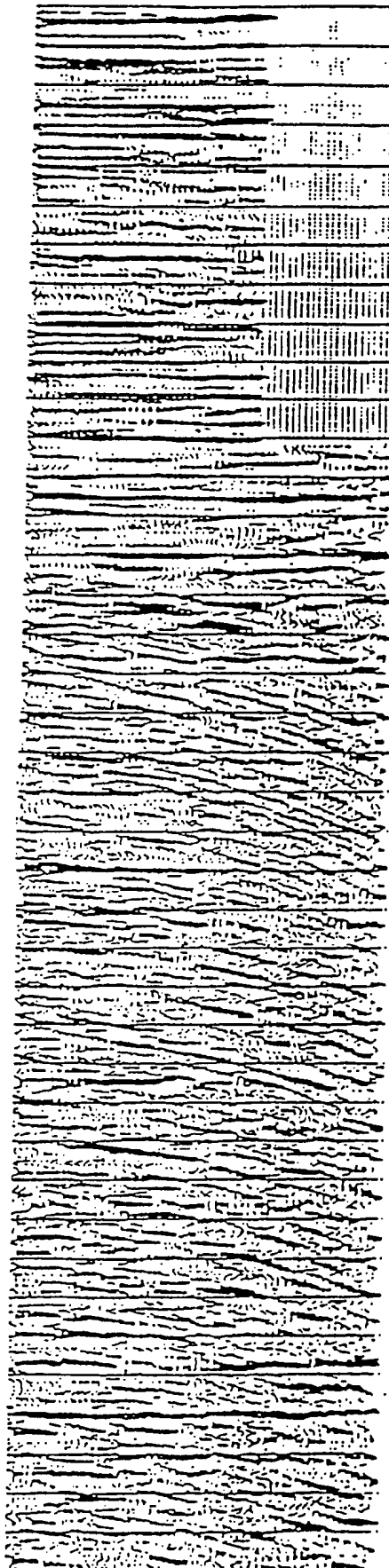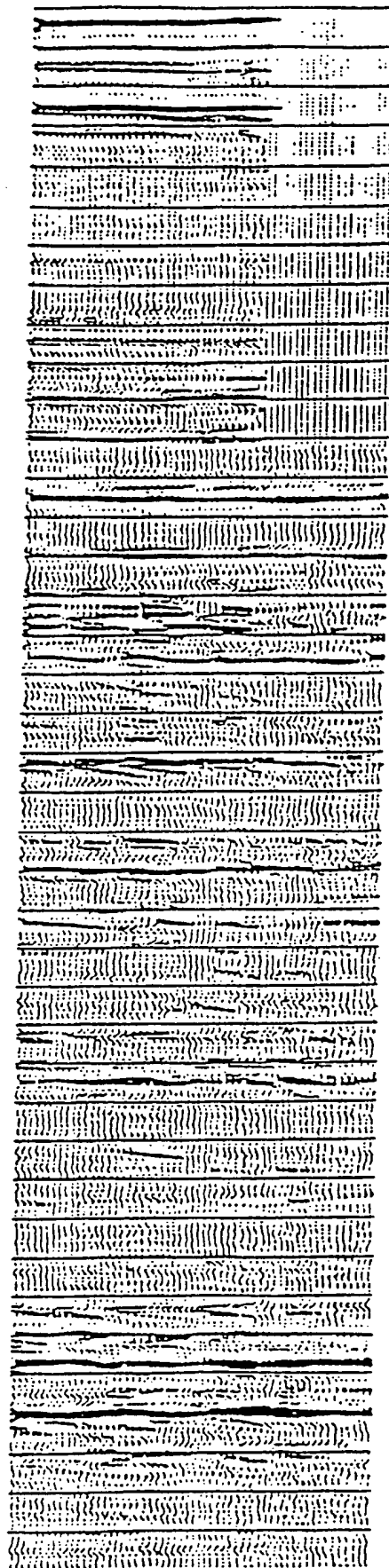
FIG. 1

2a

2b

M

P

P

2c

2d

P

3a   3b

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5

"METHOD FOR ENHANCING AND EVALUATING

SEISMIC DATA"

10   The present invention relates generally to a

method for enhancing and evaluating seismic data.

In seismic prospecting, it is conventional to

place a plurality of seismic receivers along the earth's

surface at spaced locations. A plurality of seismic

15 sources disposed at spaced locations along the earth's

surface can then be activated to generate seismic waves

which propagate outwardly in all directions. Vibrating

devices, explosive devices, and impulsive devices are

exemplary of such seismic sources. The seismic waves thus

20 generated are reflected, refracted, and diffracted from

subsurface formation interfaces and some of these diverted

seismic waves are detected by the seismic receivers and

can be processed to form a seismic signal. Such seismic

signals can be displayed as seismic sections which contain

25 information about the time, duration and intensity of the

diverted seismic waves. The seismic sections can be stu-

died to extrapolate information regarding the type and

location of subsurface formations producing the diverted

seismic waves. This information, in turn, can be employed

to evaluate the subsurface formations for oil- and gas-bearing properties.

Because of the geometry involved, seismic waves reflected from a common reflection point can be received
5 by a first seismic receiver from seismic energy generated by a first seismic source and also by a second seismic receiver from seismic energy generated by a second seismic source. These phenomena are employed in developing common depth point (CDP) seismic data. Each source and receiver
10 pair generating a seismic signal having a common reflection point has a unique range or offset (i.e., the distance separating each source and receiver pair is unique). In practice, seismic data are collected and sorted so that the seismic signals from 3-48 source and
15 receiver pairs having a common reflection point form a "CDP gather" of seismic signals.

The CDP method thus obtains multiple seismic signals for each common reflection point. Because of this redundancy, the seismic signals of a CDP gather can be
20 summed to increase signal-to-noise ratio by reinforcing coherent events within the seismic signals and suppressing random noise. Prior to summing or stacking the seismic signals of a CDP gather, the seismic signals are first processed using normal moveout correction techniques to
25 compensate for the different ray paths of the propagating seismic energy to and from a common reflection point. Summing CDP gathers of moveout corrected seismic signals can thus enhance primary reflection events in the seismic signals which correspond to the propagation of the seismic

energy along an assumed ray path to a reflecting interface
and at an assumed velocity while suppressing random noise
as well as certain multiple reflections of the seismic
energy from the reflecting interface.

5   Once seismic signals of a CDP gather are summed
so as to enhance primary reflection events and suppress
random noise and multiple reflection events, it is not
possible to retrieve the individual seismic signals in
such CDP gather for further processing. Thus, processing
10 techniques as described by Ostrander in U.S. Patents
Nos. 4,316,267 and 4,316,268 and by Bodine, et. al., in
U.S. Patent No. 4,645,239 which identify and evaluate
amplitude variations as a function of range for selected
reflection events in CDP gathers of seismic signals are
15 deprived of a powerful tool for reducing random noise and
multiple reflection events while enhancing primary
reflection events.

The techniques described by Ostrander and
Bodine, et. al., are commonly referred to as "bright spot"
20 analysis or "range dependent amplitude" (RDA) analysis.
In fact, RDA analysis techniques have proven to be a pow-
erful exploration tool through their ability to identify
seismic reflection events which are likely to correspond
to hydrocarbon-bearing formations. RDA analysis tech-
25 niques have greatly improved exploration success and thus,
the importance of utilizing RDA analysis techniques are
self-evident. In spite of the potential success to be
achieved using RDA analysis techniques, the actual use of
RDA analysis techniques is oftentimes unsuccessful because

of multiple reflection events and random noise in the
seismic data.

Prior to applying RDA analysis techniques, gain
correction techniques have generally been used to amplify
5 the seismic signals so as to compensate for temporal and
spatial variations in recorded seismic signal amplitude.
However, when gain correction techniques have been applied
to seismic data having significant random noise and/or
multiple reflection events, such gain correction tech-
10 niques can also have the undesirable effect of modifying
geologically-induced amplitude variations (as a function
of range) in the seismic data. Consequently, RDA analysis
techniques can be ineffective on seismic data having sig-
nificant random noise and/or multiple reflection events.

15 The present invention provides a novel method
for suppressing random noise and coherent noise (including
multiple reflection events) and for enhancing primary
reflection events while preserving geologically-induced
amplitude variations as a function of range for the pri-
20 mary reflection events. By suppressing random noise and
coherent noise while preserving geologically-induced
amplitude variations as a function of range for primary
reflection events, one can substantially increase the suc-
cess of employing RDA analysis techniques, whereby attri-
25 butes descriptive of amplitude variations as a function of
range can be obtained for selected primary reflection
events. Such attributes can be used to evaluate primary
reflection events for their correlation with hydrocarbon-
bearing formations.

The present invention consists in one aspect in a method for enhancing and evaluating seismic data to yield estimates of formation lithology and fluid content, comprising the steps of: suppressing random noise and coherent noise and enhancing primary reflection events, while preserving primary reflection event amplitude variations as a function of range, in a common depth point gather of seismic signals; and obtaining attributes descriptive of amplitude variations, as a function of range, for selected primary reflection events in the common depth point gather of seismic signals to yield estimates of formation lithology and fluid content.

In one embodiment of the present invention, CDP gathers of seismic signals are moveout corrected for time differences of the reflected seismic energy traveling along different assumed ray paths to and from a common reflection point. Such moveout-corrected seismic signals are stacked and an amplitude envelope is obtained from a complex signal representation of the stacked signal. A vector product is obtained of each seismic signal in the CDP gather with its corresponding stacked signal amplitude envelope to suppress random noise and coherent noise and to enhance primary reflection events whilst preserving the primary reflection events' geologically-induced amplitude variations as a function of range.

In another aspect, the present invention consists in a method for suppressing random noise and coherent noise exhibiting residual normal moveout and for enhancing primary reflection events, while preserving geologically induced amplitude variations as a function of range, in incident-angle-ordered gathers of seismic signals comprising the steps of: correcting incident-angle-ordered gathers of seismic signals for differences in travel time to and from a common reflection point; summing the corrected seismic signals and obtaining a stacked signal;

obtaining an amplitude envelope representative of the stacked signal;

and obtaining the vector product of the amplitude envelope and each

seismic signal of the incident-angle-ordered gather of seismic signals

and suppressing random noise and coherent noise exhibiting residual

normal moveout and enhancing primary reflection events while

preserving its geologically-induced amplitude variations as a function

of range.

In order to increase the effectiveness of RDA analysis

techniques, random noise and coherent noise can be suppressed in the

seismic data according to the present invention prior to the

application of either gain correction or RDA analysis techniques. Gain

correction and RDA analysis techniques can then be effectively applied

whereby attributes descriptive of the amplitude variations for

selected primary reflection events can be obtained to evaluate

formation lithology and fluid content of selected primary reflection

events.

The invention will now be described by way of example with

reference to the accompanying drawings in which:-

Figure 1 is a process flow diagram of the present invention;

Figure 2a represents a CDP gather of normal moveout corrected

seismic signals;

Figure 2b represents a stacked signal resulting from the

summation of the seismic signals of Figure 2a;

Figure 2c represents an amplitude envelope for the stacked signal

of Figure 2b;

Figure 2d represents a vector product of the amplitude envelope

of Figure 2c with each seismic signal in the CDP gather of Figure 2a;

Figure 3a represents a portion of a seismic section; and

Figure 3b represents the seismic section of
Figure 3a after processing according to the present
invention.

5   The present invention relates generally to a
method for enhancing and evaluating seismic data.

In order to facilitate a better understanding of
the present invention, the following introductory dis-
cussion is provided. In seismic data acquisition, it is
10 the usual practice to collect multiple-fold seismic data.
One such multiple-fold acquisition technique is generally
referred to as common depth point (CDP). In CDP acquisi-
tion, a plurality of seismic signals are acquired and then
sorted into CDP gathers of seismic signals having a common
15 reflection point. Each seismic signal in a CDP gather is
generated by separate pairs of seismic sources and receiv-
ers each having a unique separation distance generally
referred to as range or offset. Additionally, each seis-
mic signal of a CDP gather can be associated with a unique
20 ray path to a common reflection point and hence, have a
unique incident angle Ψ with the common reflection point.

Sorting the multiple-fold seismic data into CDP
gathers of seismic signals is merely exemplary since other
sorting techniques can be employed in the present
25 invention which sort seismic signals in order of increas-
ing or decreasing incident angle Ψ (for example, common
endpoint wherein the common endpoint is either a seismic
source or seismic receiver). All such multiple-fold seis-
mic data sets, ordered by incident angle Ψ, can be

regarded as a simple modification to the invention herein using CDP seismic data merely as an exemplar.

Both Ostrander in U.S. Patent Nos. 4,316,267 and 4,316,268 and Bodine, et. al. in U.S. Patent

5 No. 4,646,239, describe the importance of evaluating high intensity seismic events or bright spots within seismic data, all of which are incorporated by reference herein. The analysis techniques of Ostrander and Bodine, et. al. are generally referred to as "bright spot" analysis or

10 "range dependent amplitude" (RDA) analysis and are typi-cally concerned with evaluating the significance of ampli-tude variations (as a function of either range or incident angle) for selected reflection events within CDP gathers of seismic signals.

15 A critical step in such RDA analysis techniques is obtaining an accurate measure of geologically-induced amplitude variations (as a function of either range or incident angle) since such amplitude variations can be small when compared to the magnitude of the seismic

20 signal. Prior to applying such RDA analysis techniques, the seismic signals of each CDP gather are gain corrected for temporal and spatial variations in the seismic signal amplitude. However, gain correction techniques can have the undesirable effect of modifying geologically-induced

25 amplitude variations (as a function of range or incident angle) of primary reflection events, especially when the seismic data are contaminated with random noise and/or coherent noise (including multiple reflection events). As such, RDA analysis techniques oftentimes fail to provide

meaningful information because of their inability to dis-
tinguish true amplitude variations for a primary
reflection event from amplitude variations caused by
random noise or coherent noise.

5   An important aspect of the present invention
resides in a method for processing incident-angle-ordered
gathers of seismic signals to suppress random noise and
coherent noise (including multiple reflection events)
exhibiting residual normal moveout and to enhance primary

10 reflection events while preserving true amplitude vari-
ations (as a function of incident angle or range) of the
primary reflection events. Those skilled in the art will
recognize that incident angle Ψ and range can be consid-
ered equivalent because of the geometry involved. For

15 ease of further discussion, such amplitude variations will
hereafter merely be described as variations of range.

          Looking now to Figure 1, a process flow diagram
of the present invention is provided. At step 10, multi-
ple-fold seismic data are sorted into incident-

20 angle-ordered gathers of seismic signals. Although
several examples of such incident-angle-ordered gathers
have been described, preferably the multiple-fold seismic
data are sorted into CDP gathers of seismic signals,
(i.e., common reflection point).

25   At step 20, each CDP gather of seismic signals
is corrected so as to compensate for differences in travel
times of the seismic energy along different assumed ray
paths to and from a common reflection point. Such cor-
rection techniques are well understood by those skilled in

the art and are commonly referred to as normal moveout or
simply NMO. When NMO processing is done correctly, pri-
mary reflection events appear flat or horizontal across a
CDP gather of seismic signals as depicted in Figure 2a and
5 indicated by the letter P, whereas, coherent noise indi-
cated by the letter M (including multiple reflection
events) exhibiting r-sidual normal moveout and random
noise have not been so aligned.

At step 30, each CDP gather of NMO corrected
10 seismic signals is summed.or stacked along isochron lines
to obtain a stacked signal as depicted in Figure 2b. At
this juncture, the power of CDP stacking is noted wherein
random noise and coherent noise previously depicted in
Figure 2a have been substantially suppressed. However,
15 all information regarding the amplitude variations (as a
functions of range) for the primary reflection event P has
been irretrievably lost.

At step 40, a complex signal is obtained from
the stacked signal obtained in step 30. A more comprehen-
20 sive discussion of the application of complex signal anal-
ysis to seismic data is provided by M. T. Taner,
F. Koehler, and R. E. Sheriff, in "Complex Seismic Trace
Analysis," Geophysics, Volume 44, No. 6, pp. 1041-1063
(1979). Complex signal analysis treats a seismic signal
25 f(t) as the real portion of a complex signal s(t). The
complex seismic signal s(t) is composed of a real signal
f(t) and its corresponding Hilbert transform F(t), i.e.,

$$s(t) = f(t) + i \cdot F(t) \qquad\qquad (1)$$

where $i = \sqrt{-1}$.

In the present invention, $f(t)$ represents the
stacked signal and $F(t)$ is its corresponding Hilbert
transform. Thus, the complex signal $s(t)$ is a complex
representation of the stacked signal $f(t)$.

The stacked signal $f(t)$ can be expressed in
terms of a time-dependent amplitude $A(t)$ and a time-
dependent phase $\Theta(t)$ as:

$$f(t) = A(t) \cos\Theta(t) \qquad\qquad (2)$$

Similarly, the Hilbert transform $F(t)$ can be expressed as:

$$F(t) = A(t) \sin\Theta(t) \qquad\qquad (3)$$

The complex signal $s(t)$ is then:

$$s(t) = A(t) (\cos\Theta(t) + i \sin\Theta(t)) = A(t) e^{i\Theta(t)} \qquad (4)$$

Hereafter, $A(t)$ is referred to as the amplitude envelope
of the stacked signal $f(t)$. A representation of such
amplitude envelope corresponding to the stacked signals of
Figure 2b is depicted in Figure 2c. At step 50, a measure
of the amplitude envelope of the stacked signal can be
obtained employing Eqns. 1-4.

At step 60, a vector product is obtained of the
amplitude envelope A(t) and each seismic signal in its
corresponding CDP gather. Such vector product is depicted
as vector signals in Figure 2d. Here it can be now seen
5 that random noise and coherent noise have been suppressed
and the primary reflection event P has been enhanced while
preserving its geologically-induced amplitude variations
as a function of range in a CDP gather of vector signals.

An object of the RDA analysis techniques is to
10 determine amplitude variations (as a function of range)
for selected primary reflection events. If such RDA anal-
ysis techniques are done on moveout corrected data, pri-
mary reflection events appear flat within a CDP gather of
seismic signals as depicted in Figure 2a. The vector pro-
15 duct step at 60 multiplies each seismic signal across a
CDP gather of seismic signals by the same number, thereby
preserving geologically-induced amplitude variations with
range. Consequently, the relative amplitude of primary
reflection events is not modified horizontally. The
20 vector product step can be said to be linear across a CDP
gather (i.e., as a function of range) but nonlinear down
each seismic signal (i.e., as a function of time). It is
the vertical nonlinearity of the vector product step that
allows coherent noise exhibiting residual normal moveout
25 and random noise to be suppressed and allows subsequent
gain correction of the seismic data to be based on the
primary reflection events and not on random noise and/or
coherent noise.

At step 70, the resulting vector signals are
gain corrected. Gain correction techniques are used to
compensate for temporal and spatial attenuation in the
recorded seismic signal amplitude. A first gain cor-
5 rection procedure employs deterministic information about
the geometry and geology of the subterranean formation.
Such deterministic approach can be used to correct for
such things as spherical divergence filtering. This proc-
ess is usually complicated. A second and more common gain
10 correction procedure is to use statistical gain cor-
rections derived directly from the seismic data. Hereto-
fore, problems have arisen in applying statistical gain
correction techniques to seismic data having significant
coherent noise and/or random noise because such gain cor-
15 rection techniques are derived from the seismic data
including random noise and coherent noise.

Since such gain correction techniques adjust the
amplitude of the seismic data both with time and range,
the geologically-induced amplitude variations as a func-
20 tion of range of a selected primary reflection event,
after gain correction, can be adversely affected if random
noise and/or coherent noise are present in the seismic
data. For RDA analysis techniques it is thus desirable to
remove random noise and coherent noise (including multiple
25 reflection events) from the seismic data without disturb-
ing the geologically-induced amplitude variations before
applying such gain correction techniques. Failure to sup-
press random noise and coherent noise while preserving
geologically-induced amplitude variations (as a function

of range) of selected primary reflection events before gain correction can adversely affect RDA analysis techniques.

Having now obtained CDP gathers of gain-corrected signals wherein random noise and coherent noise exhibiting residual normal moveout have been suppressed and primary reflection events have been enhanced while retaining their geologically-induced amplitude variations as a function of range, RDA analysis techniques can be employed at step 80 to obtain information about formation lithology and fluid content related to such amplitude variations for selected primary reflection events.

By way of example, the RDA analysis techniques of Bodine, et. al. can be employed to obtain attributes descriptive of such range amplitude variations. Here, measures of the amplitude for selected primary reflection events in a CDP gather of gain-corrected signals are statistically fit to equations such as:

$$R_c(\Psi) = B_0 + B_1 \tan^2\Psi + B_2 \sin^2\Psi \tan^2\Psi \qquad (5)$$

where $R_c(\Psi)$ is a measure of a reflection coefficient for selected primary reflection events (as a function of incident angle);

B_0, B_1, and B_2 are attributes descriptive of amplitude variations as a function of incident angle; and

Ψ is a measure of the incident angle for each assumed ray path from a common reflection point.

The attributes (B_0, B_1, and B_2) thus obtained
can be successfully employed to evaluate formation lithol-
ogy and fluid content. In fact, the present invention has
substantially improved the ability to employ RDA analysis
5 techniques such as Bodine, et. al.

At step 90, the gain corrected signals of
step 70 can be studied for each CDP gather and a plurality
of such stacked signals can be plotted as CDP seismic sec-
tions. Looking now to Figures 3a and 3b, two seismic sec-
10 tions are represented. The seismic section of Figure 3a
represents seismic data processed according to conven-
tional CDP processing techniques. The seismic data of
Figure 3b represents the same seismic data of Figure 3a
after processing according to steps 10-70 described above
15 wherein the resulting vector signals have been stacked to
produce a new CDP section.

While the present invention has been described
in specific steps, it is contemplated that those skilled
in the art may substitute additional or modified steps
20 without departing from the scope of the invention which is
limited only by the appended claims.

25

CLAIMS:

    1. A method for enhancing and evaluating seismic data to yield estimates of formation lithology and fluid content, comprising the steps of:

5   (a) suppressing random noise and coherent noise and enhancing primary reflection events, while preserving primary reflection event amplitude variations as a function of range, in a common depth point gather of seismic signals; and

10   (b) obtaining attributes descriptive of amplitude variations, as a function of range, for selected primary reflection events in the common depth point gather of seismic signals to yield estimates of formation lithology and fluid content.

15   2. The method of Claim 1 wherein the step of suppressing random noise and coherent noise in a common depth point (CDP) gather of seismic signal comprises the steps of:

     (a) summing the seismic signals of the CDP

20 gather and obtaining a stacked signal;

     (b) obtaining an amplitude envelope for the stacked signal;

     (c) obtaining vector signals representative of the product of the amplitude envelope of

25 the stacked signal and each seismic signal of the CDP gather.

    3. The method of Claim 1 wherein the step of enhancing primary reflection events, while preserving the primary reflection event amplitude variations as a func-

tion of range, in a common depth point (CDP) gather of
seismic signals comprises the steps of:

(a) summing the seismic signals of the CDP
gather and obtaining a stacked signal;

5   (b) obtaining an amplitude envelope for
the stacked signal; and

(c) obtaining vector signals represen-
tative of the product of the amplitude envelope in
each seismic signal of the CDP gather.

10   4. The method of Claim 1 wherein the step of
suppressing random noise and coherent noise and enhancing
primary reflection events, while preserving the primary
reflection event amplitude variations as a function of
range, in a common depth point (CDP) gather of seismic
15 signals comprises the steps of

(a) summing the seismic signals of the CDP
gather obtaining a stacked signal;

(b) obtaining an amplitude envelope for
the stacked signal; and

20   (c) obtaining vector signals represen-
tative of the product of the amplitude envelope in
each seismic signal of the CDP gather.

5. The method of Claims 2, 3, or 4 wherein the
amplitude envelope is obtained from the stacked signal
25 according to:

$$f(t) = A(t) \cos\Theta(t) \hspace{2cm} (6)$$

where $f(t)$ = stacked signal;

$\Theta(t)$ = time dependent phase of the stacked signal; and

$A(t)$ = amplitude envelope of the stacked signal.

6. The method of Claims 2, 3, or 4 wherein the step of obtaining the amplitude envelope comprises the steps of:

(a) obtaining a complex signal representative of the stacked signal; and

(b) obtaining an amplitude envelope of the complex signal.

7. The method of Claim 1 wherein the step of obtaining attributes comprises the steps of:

(a) gain correcting seismic signals of the CDP gather to compensate for temporal and spatial variations in seismic signal amplitude; and

(b) statistically fitting the gain corrected seismic signal amplitudes to:

$$R_c(\Psi) = B_0 + B_1 \tan^2\Psi + B_2 \sin^2\Psi \tan^2\Psi \qquad (7)$$

where $R_c(\Theta)$ = reflection coefficient as a function of incident angle;

B_0, B_1 and B_2 are attributes descriptive of the amplitude variations as a function of range; and

Ψ = incident angle.

8. A method for suppressing random noise and coherent noise exhibiting residual normal moveout and for enhancing primary reflection events, while preserving geo-

logically induced amplitude variations as a function of range, in incident-angle-ordered gathers of seismic signals comprising the steps of:

(a)   correcting incident-angle-ordered
5   gathers of seismic signals for differences in travel-time to and from a common reflection point;

(b)   summing the corrected seismic signals and obtaining a stacked signal;

(c)   obtaining an amplitude envelope repre-
10   sentative of the stacked signal; and

(d)   obtaining the vector product of the amplitude envelope and each seismic signal of the incident-angle-ordered gather of seismic signals and suppressing random noise and coherent noise exhibit-
15   ing residual normal moveout and enhancing primary reflection events while preserving its geologically-induced amplitude variations as a function of range.

9.   The method of Claim 8 wherein step (c) includes the steps of:

20   (a)   obtaining a complex signal represen-tation of the stacked signals; and

(b)   obtaining an amplitude envelope of the complex signal.

10.   The method of Claim 8 wherein the inci-
25   dent-angle-ordered gather of seismic signals includes common depth point gathers and common end point gathers.

11.   A method for enhancing and evaluating seismic data substantially as hereinbefore described with reference to the accompanying drawings.